Harmonizing Estimates of Forest Land Area from National-Level Forest Inventory and Satellite Imagery

Bonnie Ruefenacht[1], Mark D. Nelson[2], Mark Finco[1], Ken Brewer[1]

Abstract: *Estimates of forest land area are derived both from national-level forest inventories and satellite image-based map products. These estimates can differ substantially within subregional extents (e.g., states or provinces) primarily due to differences in definitions of forest land between inventory- and image-based approaches. We present a geospatial modeling approach for redefining satellite image-based pixels to meet inventory definitions. We compare resulting estimates of forest land area for six test states – Arizona, Minnesota, Montana, New York, North Carolina, and Oregon – using image estimates based on Moderate Resolution Imaging Spectroradiometer (MODIS) and inventory estimates from the U.S. Department of Agriculture Forest Service's Forest Inventory and Analysis Program (FIA). Our geospatial model utilizes several ancillary geospatial datasets to simulate conditions required by FIA's definition of forest land, including minimum forest patch area and width, minimum tree stocking or canopy cover, and exclusion of lands not used primarily as forest land.*

Keywords: forest, inventory, land use, land cover, dasymetric mapping, FIA

Introduction

Forest Inventory and Analysis

The mission of the USDA Forest Service Forest Inventory and Analysis Program (FIA) is to inventory the renewable forest and rangeland resources of the US. To inventory these resources, FIA has established field sample plots throughout the US at an intensity of approximately one plot per 2,400 ha (6,000 acres) (USDA Forest Inventory and Analysis 2007). FIA uses an annual rotating panel system whereby between 10 to 20 percent of each state's plots are sampled every year. From this plot data, FIA produces annual estimates of forest land area, reported in the form of tabular data at the county and state level. FIA defines forest land as land that meets at least one of the two following criteria:

[1] USDA Forest Service Remote Sensing Applications Center, 2222 West 2300 South, Salt Lake City, UT 84119
[2] USDA Forest Service Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108

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1. The land is at least ten percent stocked by trees of any size or has been at least ten percent stocked in the past. It is not subject to non-forest use(s) that prevent normal tree regeneration and succession such as regular mowing, grazing, or recreation activities. The area stocked by trees is at least one acre in size and at least 120 feet wide.
2. The land is a western woodland type where stocking cannot be determined, and has at least five percent crown cover by trees of any size, or has had at least five percent cover in the past. Additionally, the land is not subject to non-forest use(s) that prevent normal regeneration and succession such as regular mowing, grazing, or recreation activities. The area stocked by trees or with five percent crown cover is at least one acre in size and at least 120 feet wide.

Conversely, non-forest land is defined by FIA as land that does not support, or has never supported forests, and lands formerly forested where use for timber management is precluded by development for other uses. Non-forest land includes areas used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining rights-of-way, power line clearings of any width, and non-census water. If intermingled in forest areas, unimproved roads and non-forest clearings must be more than 120 ft wide or more than one acre in size to qualify as non-forest land. Structures such as houses and cabins are considered non-forest land regardless of the size of the housing unit.

Although FIA forest land and non-forest land often are referred to in terms of "land use", FIA definitions reveal components of both land use and land cover. Requirements for minimum tree stocking or crown cover, minimum patch size, and minimum patch width all refer to land cover characteristics. Presence or absence of specific human activities (e.g., clearing of power line rights-of-way, or mowing of city parks) refers to land use characteristics. In addition, a temporal component is inherent within FIA's definitions: previously forested lands continue to be defined as forest following removal of tree canopy (e.g., from harvest, fire, or windstorm) if those lands have not been converted to another use and future tree regeneration is expected to achieve minimum thresholds of stocking or crown cover. FIA forest land is further differentiated into three sub-components: timberland, reserved forest land, and other forest land, which are defined by forest productivity and protection status.

Satellite Image-Based Land Cover Classification

Satellite imagery incorporates large geographic extents and commonly is used for mapping land cover. Land cover classifications typically include all landscape entities such as urban areas, forests, shrublands, grasslands, open water, etc. Usually these map products are defined in terms of land cover such as the National Land Cover Database (NLCD) of 2001 (Homer and others 2007). However, a seminal classification system for remotely sensed data (Anderson and others 1976) refers to both land use and land cover, as do many current assessments of "land use/land cover" change and trends.

Nelson and others (2005) explored the efficacy of satellite image-derived maps for estimating forest land area by comparing estimates obtained from FIA, the USDA Natural Resources Conservation Service's (NRCS) National Resources Inventory (NRI), and four satellite image-derived data sets: 1991 Forest Cover Types, 1992–93 Land Cover Characteristics, 2001 Vegetation Continuous Fields, and the 1992 NLCD. The four satellite image-derived land cover maps, differing in date of image acquisition, classification scheme, and spatial resolution, showed varying degrees of similarity with inventory estimates of forest land across the conterminous United States (CONUS).

Forest Land Cover and Land Use

Both FIA and satellite image-based classifications may include components of land cover and land use but the importance of cover vs. use differs between these approaches. Therefore, a mapping approach for differentiating forest land use versus forest land cover would provide a more consistent basis for comparing classified satellite imagery with FIA estimates of forest land area. This topic comprises components of a broader research project being conducted by FIA and the Forest Service Remote Sensing Applications Center to produce a "four-in-one" geospatial dataset of pixel predictions for percent 1) tree canopy cover, 2) forest cover, 3) forest use, and 4) subcomponents of FIA forest land.

Nelson and others (2004) addressed the first component – tree canopy cover – by calibrating satellite image-based per-pixel predictions of percent tree canopy cover such that resulting estimates of forest land area were comparable to FIA estimates. Canopy cover is defined as "the proportion of the forest floor covered by the vertical projection of the tree crowns" and canopy closure is defined as "the proportion of the sky hemisphere obscured by vegetation when viewed from a single point" (Jennings and others 1999). Although terms such as crown closure, crown cover, and canopy closure sometimes are used interchangeably, (e.g., Avery and Burkhart 1994), we use the term canopy cover as defined in Jennings and others (1999). Although per-state estimates of forest land area derived from tree canopy cover data were strongly and positively correlated with FIA estimates, the two were not equivalent, due in part to definitional differences in land cover and land use.

The fourth component – differentiating timberland, reserved forest land, and other forest land – has been addressed by combining geospatial datasets of forest inventory attributes, forest land cover, and land ownership and protection (Nelson and Vissage 2007).

The focus of this study is to address the second and third components of the "four-in-one" project – forest cover vs. forest use – by using existing geographic information systems (GIS) / remote sensing data layers to produce a map of forest land for the conterminous United States (CONUS), corresponding to FIA's definition of forest land. The initial map product is designed to have spatial resolution of 250 m, although the modeling procedure was designed to allow for production of forest maps having other spatial resolutions. Six states were chosen to develop and test the methodology: Arizona, Minnesota, Montana, New York, North Carolina, and Oregon. The subject of this paper is the development of the forest land use product for these six states.

Methods

An overview of the geospatial modeling process is presented below, and is diagrammed in the flowchart in figure 1. Following this overview is a more in-depth description of the methodology for specific land cover components.

FIA forest land is characterized by minimum tree stocking or crown cover, minimum patch area and width, and absence of non-forest uses. Non-forest land is defined in terms of agriculture lands, roads, urban areas, water, and small patch area or width. GIS and remote sensing data layers that characterize non-forest land cover classes already exist for CONUS. Therefore, forest land can be characterized and mapped by eliminating everything that is not non-forest land.

A raster tree canopy cover data layer was filtered to serve as a surrogate for FIA tree stocking/crown cover. Because the tree canopy dataset used in this study had coarser spatial resolution (250 m) than the other land cover datasets (30 m), a dasymetric mapping procedure was employed to spatially reallocate tree canopy cover to only areas with potential tree cover within the 250 m pixels so that accurate percent tree canopy cover estimates could be made.

The first step involved selection of land cover pixels where trees could potentially grow; trees cannot grow or are prohibited from growing on several land cover types (e.g., roads, water, and agricultural lands). GIS and remote sensing data layers of these land cover classes were combined and labeled as non-forest; everything else was labeled as potential forest.

Within each canopy cover pixel, non-forest cover pixels were labeled as non-tree cover; remaining areas were labeled as potential tree cover. The percent tree canopy cover attributed to the coarser pixel was reallocated to represent a more spatially explicit distribution of tree canopy cover within each pixel. This "true" "canopy cover layer was used to eliminate areas of potential forest that did not meet the minimum threshold. Initial GIS processing was conducted in a vector file format. This procedure was compared with a raster-based approach, which was used thereafter.

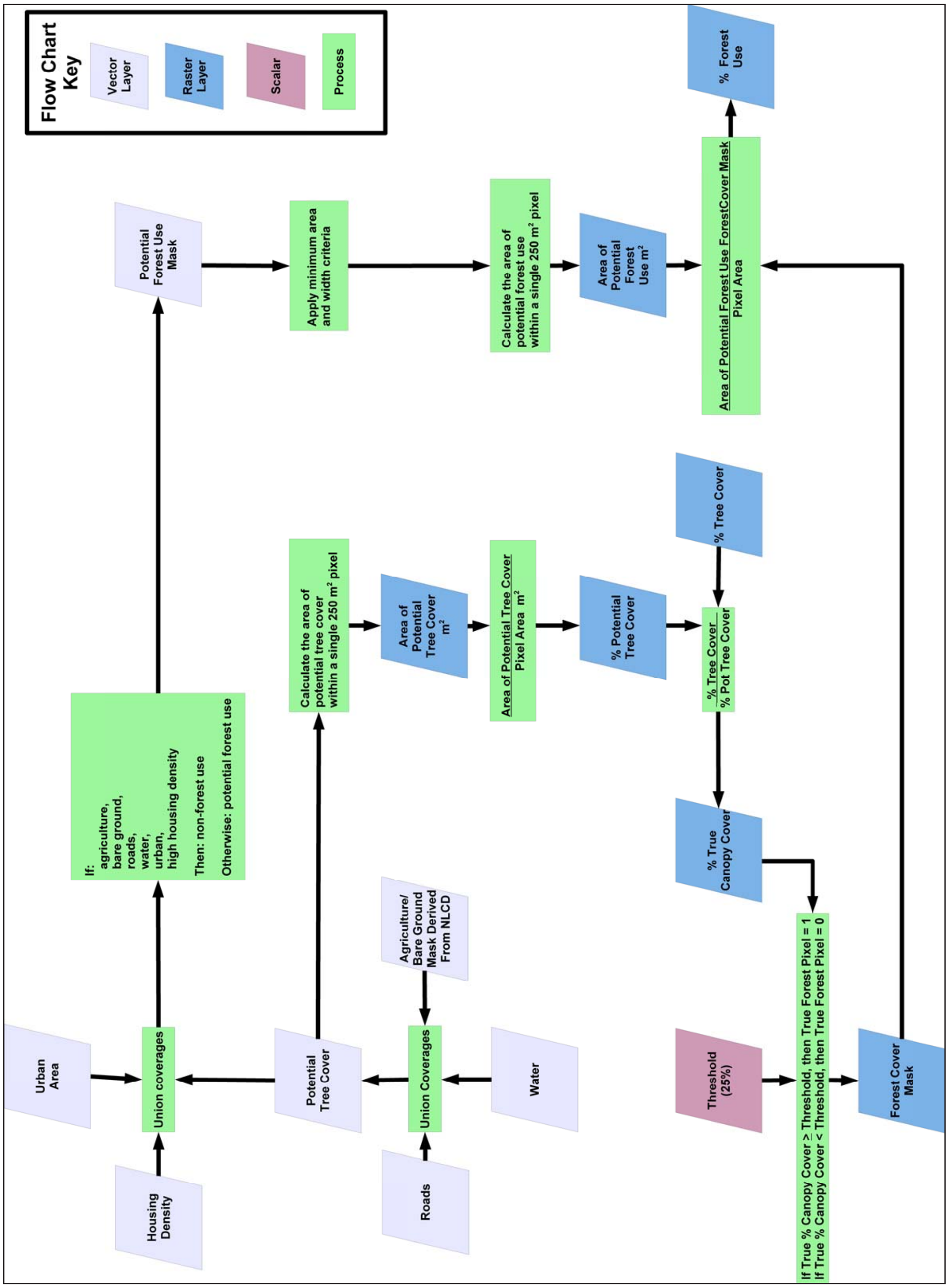

Figure 1: Flowchart depicting the process used to create the percent forest use product.

Non-Forest Land Use

Agriculture Lands: The database used to delineate agriculture lands was the 2001 NLCD (Homer and others 2007), which categorizes the entire U.S. at a spatial resolution of 30 m into 29 land cover classes (http://landcover.usgs.gov). The classes of interest to this project were 81 (pasture/hay), 82 (cultivated crops), and 31 (barren). Overall classification accuracies reported for 2001 NLCD ranged from 70 to 98 percent across mapping zones, with a nationwide average accuracy of 83.9 percent (Homer and others 2007). To create an agriculture/bare land mask, pixels with codes 31, 81, or 82 were recoded to a value of "1"; everything else was recoded to value of "0". The agriculture/bare land mask was converted to a polygon coverage.

Roads: The roads database, which is a line coverage at a scale of 1:100,000, was obtained from the Bureau of Transportation Statistics (http://www.bts.gov). Roads are attributed as indicated in the first two columns of table 1. According to FIA's non-forest land definition, unimproved roads that are intermingled in forest areas and less than 120 feet wide are considered forest land. Four-wheel-drive (4WD) trails generally are narrow and unimproved, meaning that they are not typically defined as non-forest. Therefore, these roads, with FCC codes A5 - A53, were deleted from the roads database. Since roads in the database are represented as centerlines that have no inherent width, the lines were buffered according to the road widths shown in table 1. These road widths were either derived from federal road standards or from general accepted standards of road widths.

Table 1: Road Attributes and assigned widths

FCC	Road Type	Total Road Width
A1 – A18	Interstate Highways	86 ft
A2 – A29	State Highways	44 ft
A3 – A38	City Main Thoroughfares	30 ft
A4 – A48	Local Roads	20 ft
A5 – A53	4WD Trails	10 ft
A61	Cul-de-Sac	120 ft
A62	Traffic Circle	120 ft
A60, A63	Access Ramps	26 ft
A64	Service Road	10 ft
A7 – A73	Other	10 ft

Water: The water data layer was extracted from the Wildland-Urban Interface (WUI) database (http://silvis.forest.wisc.edu/projects/WUI_Main.asp), which is based on the U.S. Census Bureau TIGER line files. The scale of the water data layer is 1:100,000.

Urban Areas/Structures: The smallest geographic entity for which the U.S. Census Bureau tabulates decennial data is the census block (http://www.census.gov). Aggregations of blocks are termed block groups. Blocks and block groups are irregular in shape and vary in size. Urbanized areas (UA) and urban clusters (UC) portray aggregations of core blocks or block groups that have a population density of at least 1,000 people per square mile, and surrounding blocks or block groups that have an overall density of at least 500 people per square mile. The UA and UC areas were considered to be non-forest. Census UA/UC data layers address population centers, but do not include rural areas. In addition, houses rarely are evenly distributed within census blocks or block groups. Normally, houses are located close to roads and are not located on steep slopes. Using the roads database described above, roads were buffered by 300 feet to capture a zone of proximity in which most housing structures are expected to be located.

A data layer of topographic slope from the USGS Elevation Derivatives for National Applications (EDNA) (http://edna.usgs.gov/) was used to produce a slope mask, where a value of "1" indicated areas less than 15 degrees of slope and a value of "2" indicated areas greater than or equal to 15 degrees of slope.

The slope mask and the road buffer data layers were joined together to predict locations of housing structures for areas outside the urban areas and urban clusters. Using a housing density attribute in the WUI database, the number of houses in each census block was redistributed to a geographic subset of each block occurring within the zone of road buffers, where slopes were less than 15 degrees. This dasymetric mapping approach was used to recalculate housing density within non-steep road buffers. Raster cells then were assigned their corresponding housing density value. If the resulting housing density was less than one house per ten acres, then the area was considered to be undeveloped. Otherwise, the area was considered to be developed and defined as non-forest.

The non-forest land use products described above are used in the development of the potential tree cover data layer discussed in the next section.

Tree Cover

Potential Tree Cover: A data layer representing non-treed lands was created by combining data layers for agriculture lands, road buffers, and water, described above. Remaining areas were assumed to have potential for growing trees. The potential tree cover data layer is used in the development of the potential forest data layer described in the next section.

Percent Potential Tree Cover: The next step was to calculate the areal extent of potential tree cover within each 250 m x 250 m cell, using the Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m Vegetation Continuous Fields (VCF) percent tree canopy cover dataset. The VCF dataset consists of per-pixel predictions of woody vegetation, herbaceous vegetation, and bare ground, which together sum to a total of 100 percent cover for each pixel. The VCF data layer of interest to this project is woody vegetation, i.e., tree canopy cover, which will be referred to simply as VCF for the remainder of this document.

Using VCF and the PIXELX and PIXELY functions in the ERDAS Imagine software package, a raster product was created where each pixel had a unique value based on the spatial location of the cell. This raster product was converted to a polygon coverage consisting of 250 m x 250 m squares. This polygon coverage was joined with the potential tree cover data layer making possible the calculation of area of potential tree cover occurring within each square polygon. This product was converted to a raster with a spatial resolution of 250 m. The area values were converted to percentages, thereby creating a percent potential tree cover data layer.

Area-Weighted Canopy Cover: VCF percent tree canopy cover values represent per-pixel predictions. However, canopy cover can vary substantially within each pixel because source MODIS pixels are coarse in spatial resolution relative to patterns of forest structure. For example, a VCF cell value might be 30% but this does not imply that woody vegetation is evenly distributed, at a density of 30%, throughout the cell.

To calculate the "true" canopy cover of the cell, the VCF per-pixel prediction of percent tree canopy cover was divided by the percent potential tree cover. If the percent potential tree cover was 100% and the VCF value was 30%, the woody vegetation was assumed to be evenly distributed throughout the cell and the "true" canopy cover is also 30%. If, however, only 50% of the cell has potential tree cover and the VCF value was 30%, then the VCF value is reallocated to the half of the cell with potential tree cover and the area-weighted prediction of canopy cover for that cell is 60% (i.e., 30/50).

Forest Cover Mask: A minimum threshold of tree stocking (or crown cover) must be present to meet FIA's definition of forest land. Because no geospatial dataset of tree stocking was available, the area-weighted canopy cover dataset was used as a surrogate. To satisfy the stocking requirement, a 25% minimum threshold of canopy cover was employed. If the area-weighted canopy cover for a pixel was below the threshold, the pixel was assigned a "0". Otherwise, the pixel was assigned a "1". This forest cover mask dataset was used to remove areas of non-forest land from the forest land in the next section.

Forest Land

Potential Forest: Potential forest was modeled by combining the potential tree cover data layer with the urban areas/structures data layer. Pixels were labeled as potential forest if they had potential tree cover and were not labeled as developed.

Minimum Acreage and Width: The next step was to eliminate areas from the potential forest data layer that were too small or too narrow, according to FIA's definition. All forest polygons smaller than one acre were relabeled as non-forest. Forested areas that were less than 120 feet wide were relabeled as non-forest. Because of coverage processing limitations, all procedures were performed on geographic subsets of data that measured 150 km x 150 km in extent.

FIA Forest Land: The resulting data layer produced from the steps above was joined with the 250 m x 250 m polygon grid created previously making possible the calculation of area of potential forest land occurring within each square polygon. This product was converted to a raster with a spatial resolution of 250 m and the area values were converted to percentages. The forest cover mask described above was used to remove pixels with less than 25% area-weighted canopy cover. These steps created a percent forest use or percent forest land data layer. The percent forest use data layers for Arizona, Minnesota, Montana, New York, North Carolina, and Oregon are displayed in Figures 2 – 7.

FIA produces tabular county summaries for various forest attributes which are estimated using sample plot measurements. These estimates are made available to the public as published reports and via web-based estimation tools such as Forest Inventory Data Online, EVALIDator, and FIA MapMaker (http://www.fia.fs.fed.us/tools-data/). FIA forest land area estimates were compiled for the states and counties for each of the six states included in this study. Corresponding estimates of sampling errors were used to construct 95 percent confidence intervals surrounding per-state estimates.

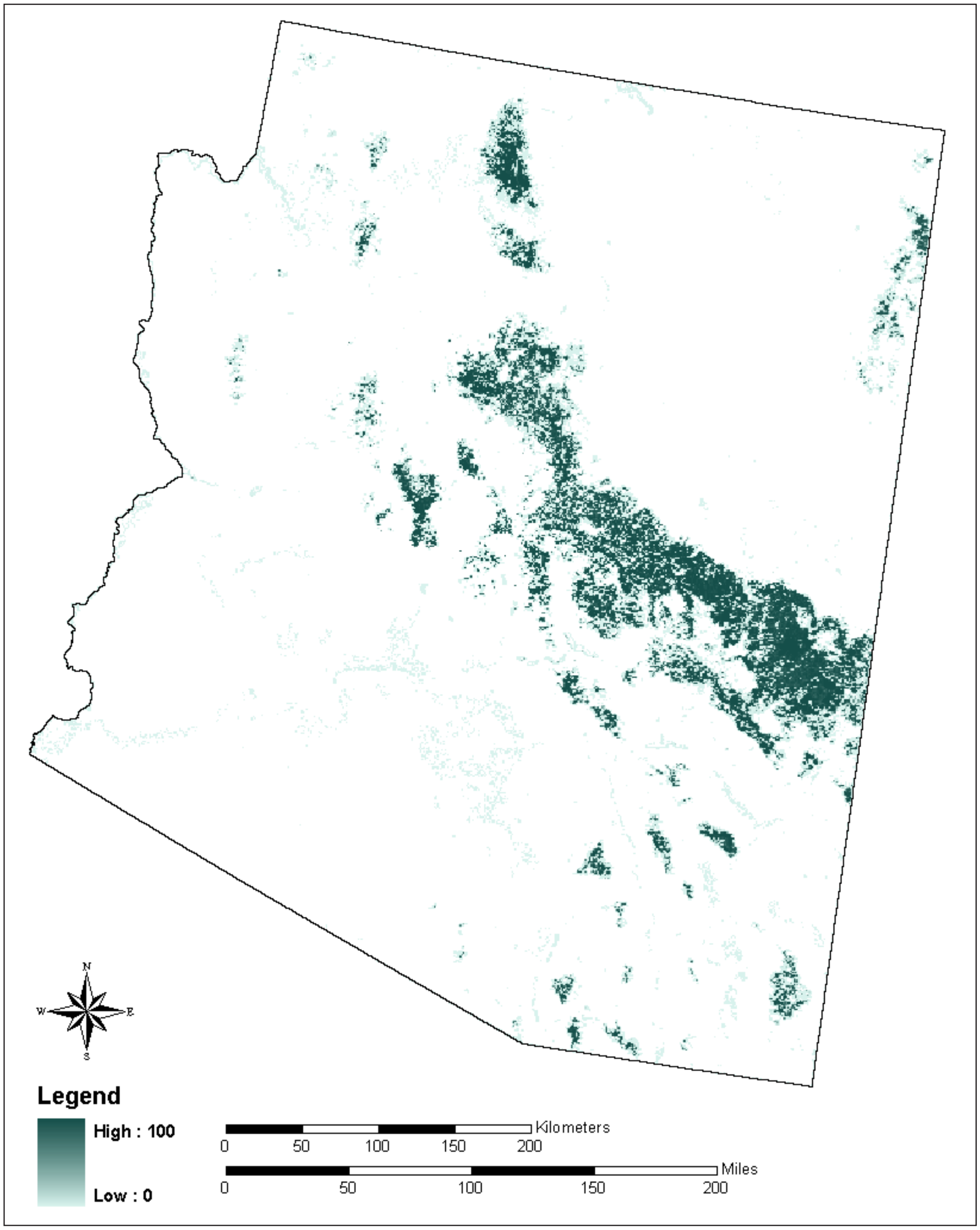

Figure 2: Percent forest use at 250 m spatial resolution of Arizona.

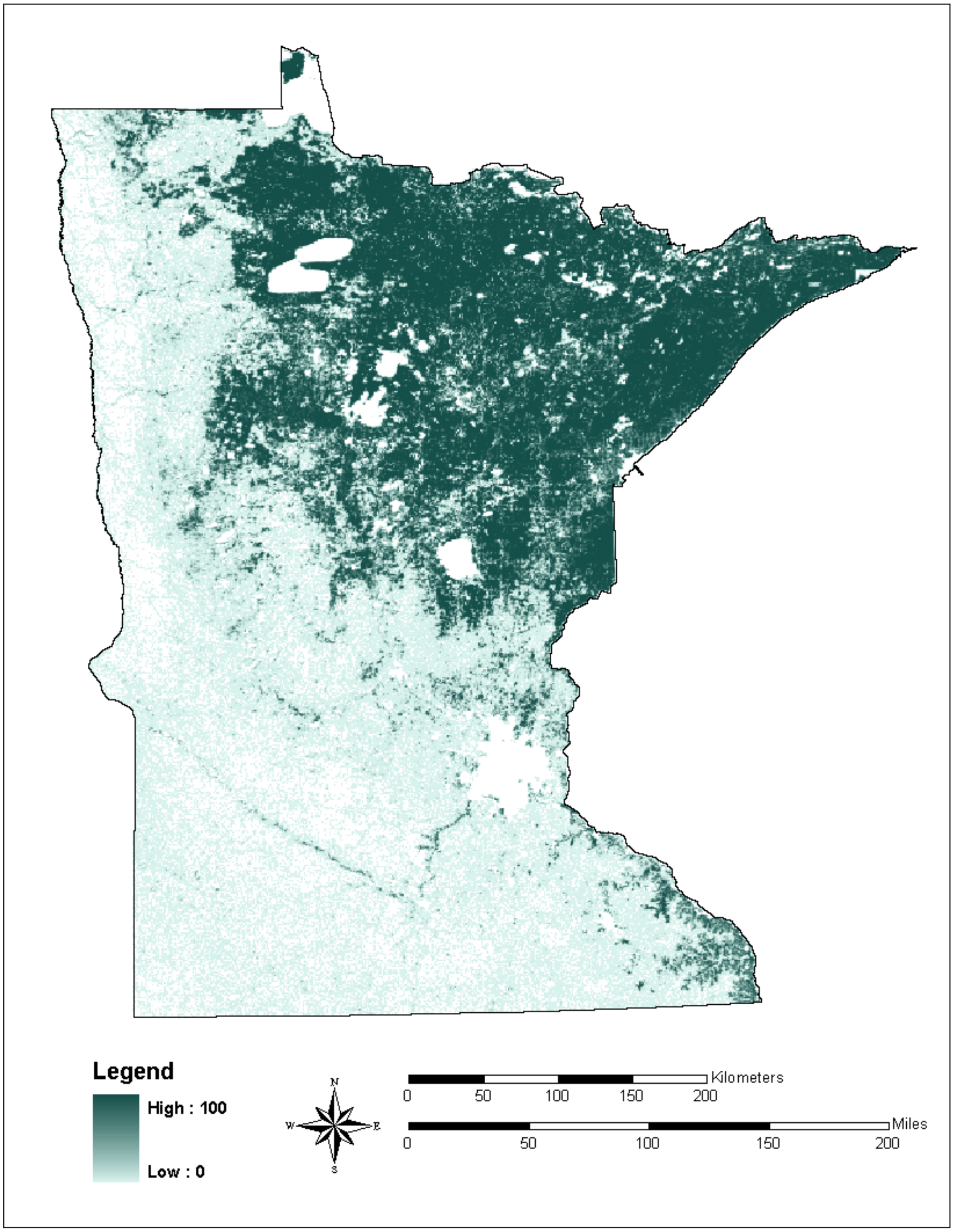

Figure 3: Percent forest use at 250 m spatial resolution of Minnesota.

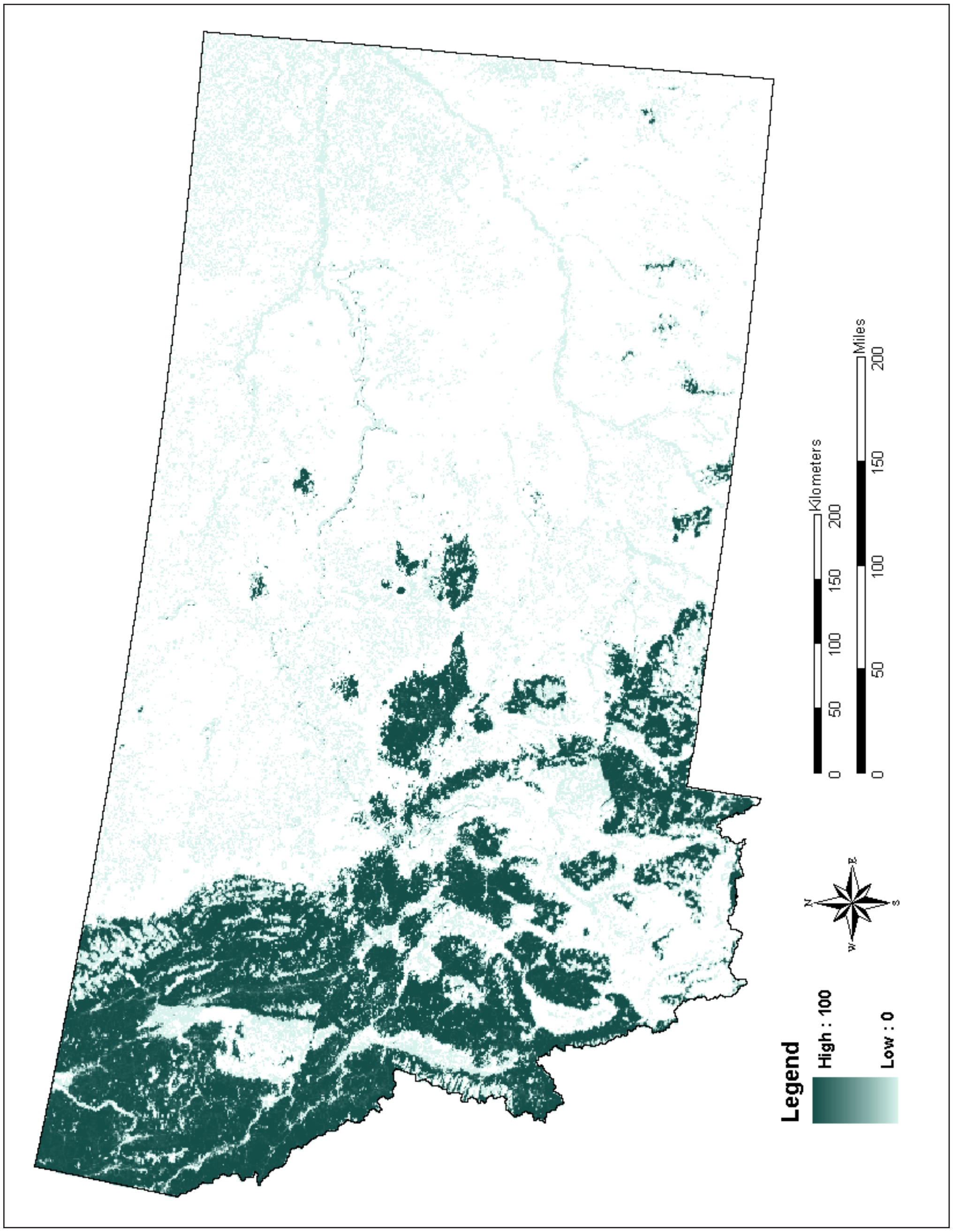

Figure 4: Percent forest use at 250 m spatial resolution of Montana

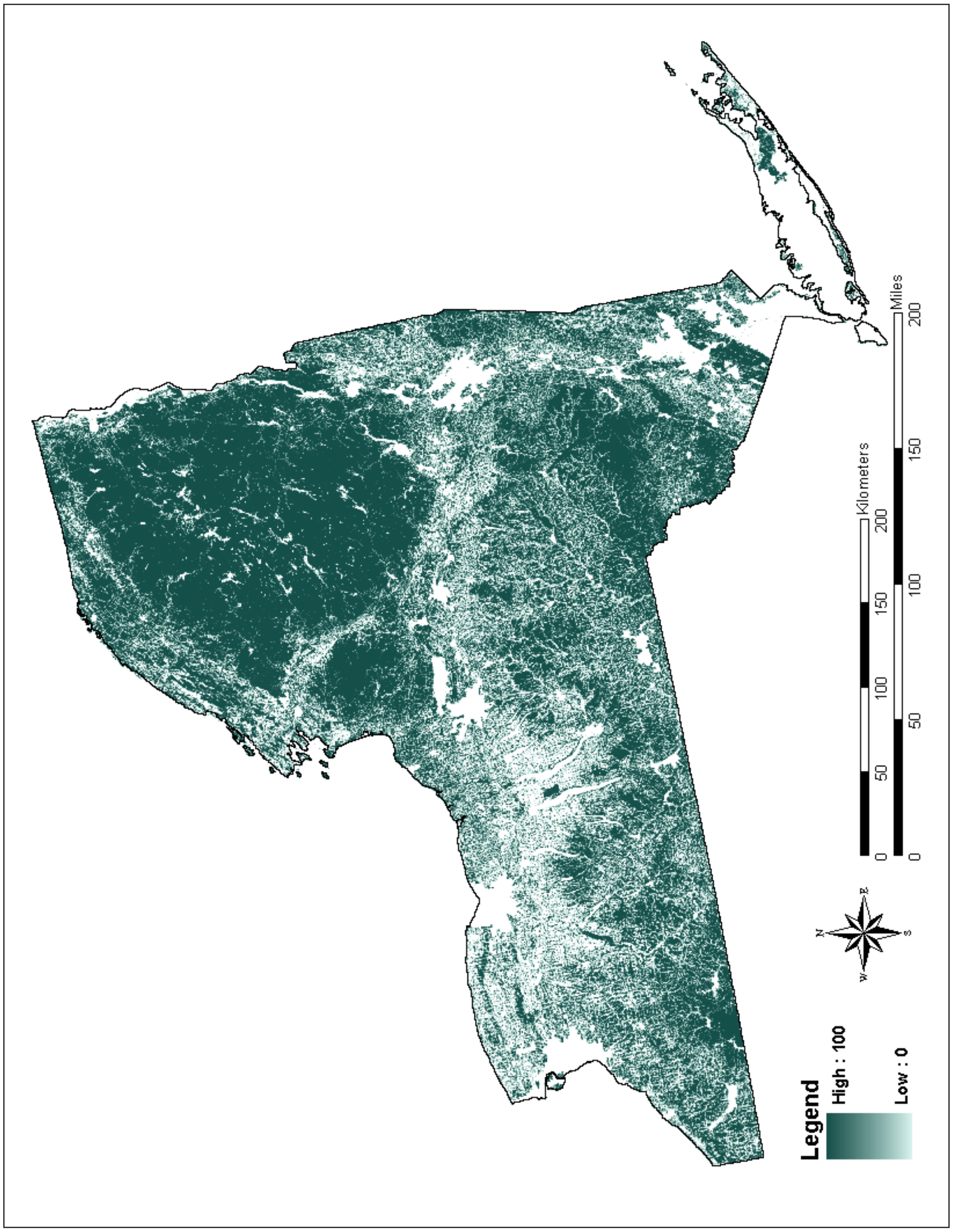

Figure 5: Percent forest use at 250 m spatial resolution of New York.

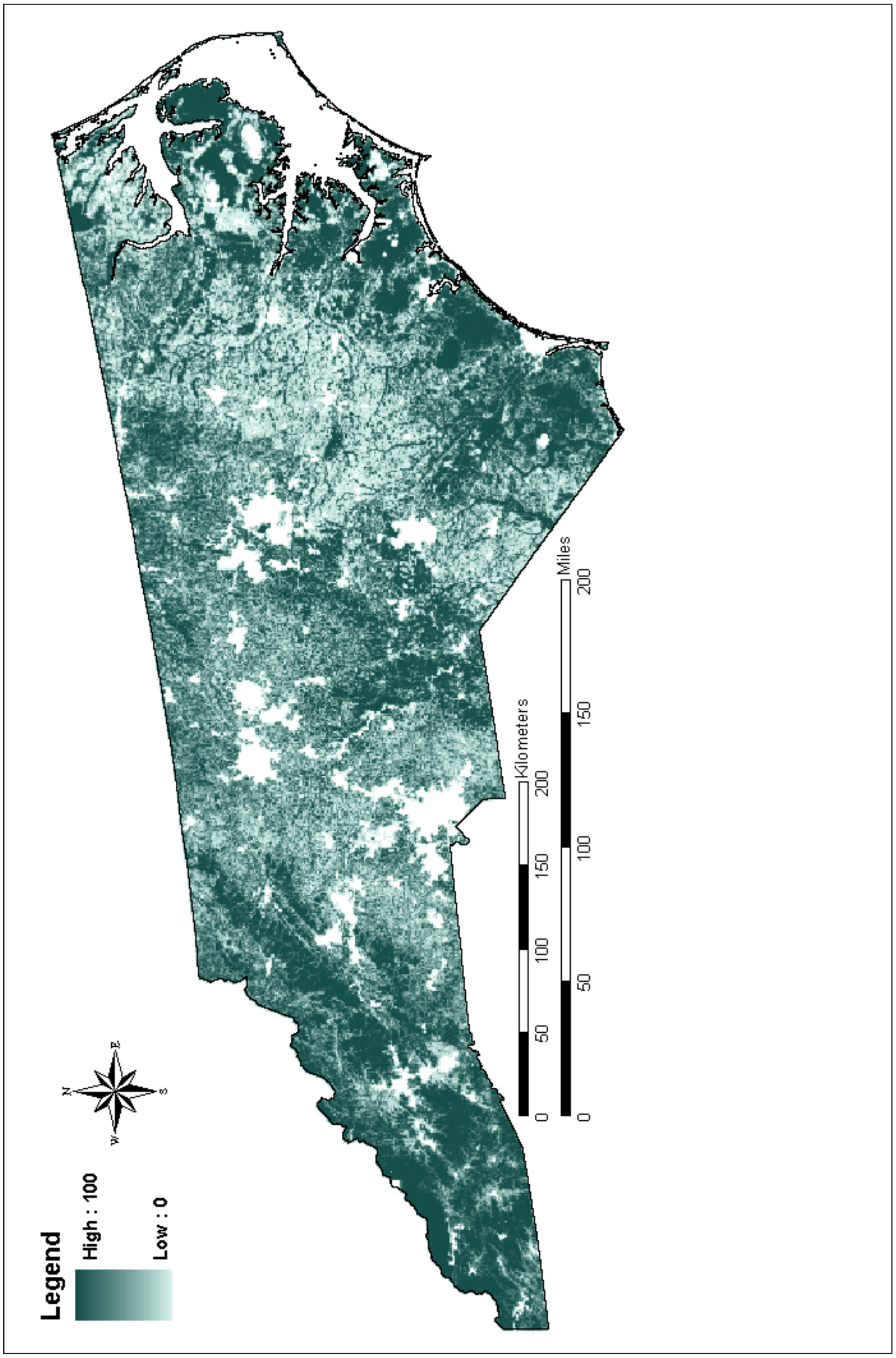

Figure 6: Percent forest use at 250 m spatial resolution of North Carolina.

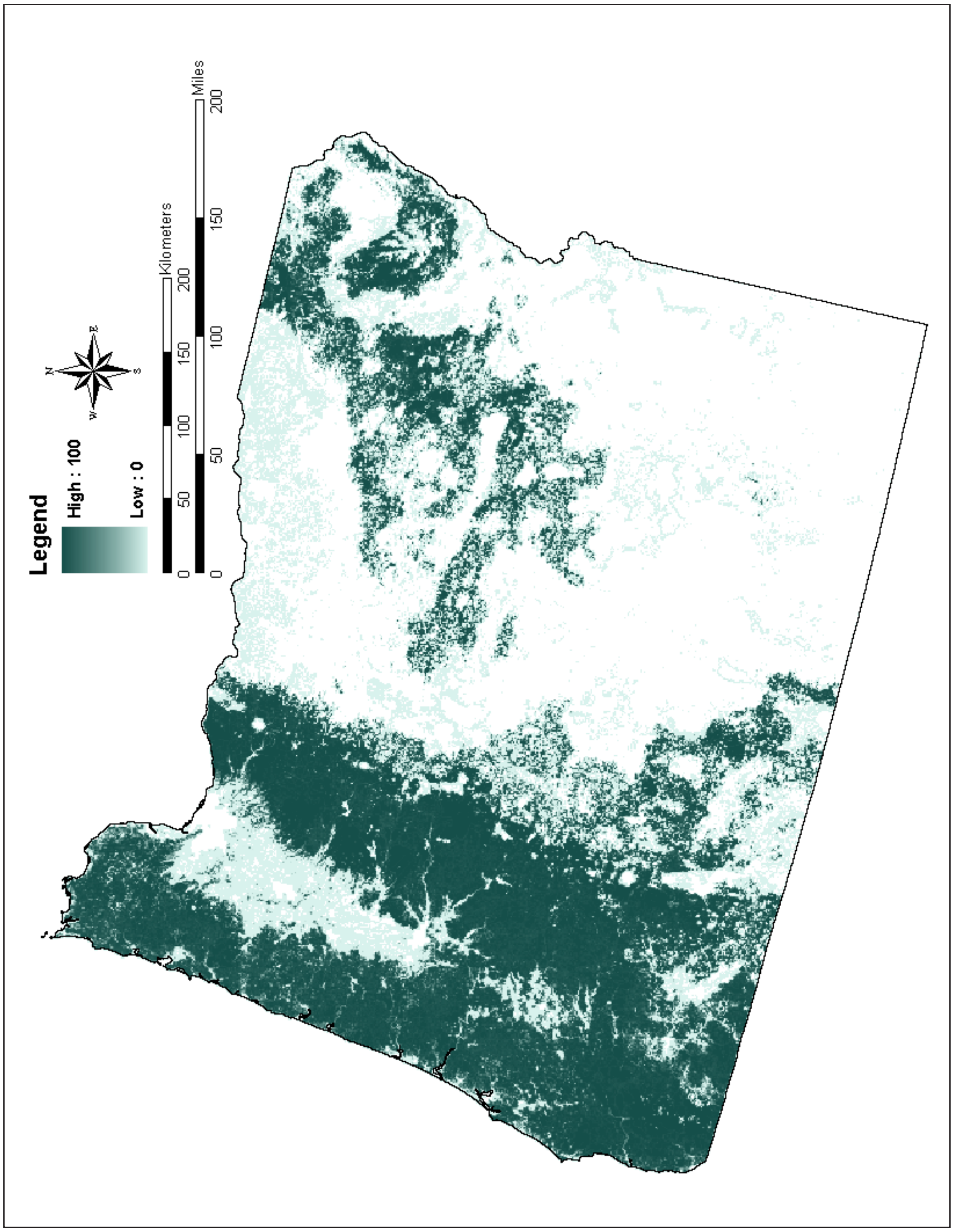

Figure 7: Percent forest use at 250 m spatial resolution of Oregon.

GIS Processing Effects

A major technical question is: can a geospatial forest map product be produced using a raster GIS file format, rather than the vector GIS file format employed in this study? Due to improved processing efficiency, working in a raster environment would eliminate the need to subset databases and could greatly reduce computer processing time. However, some vector processes cannot be replicated in a raster environment, or may produce different results (Wade and others 2003). For example, the reallocation of WUI housing density to different size polygons is a vector operation and raster data do not have polygons. Also, the elimination of areas less than 120 feet wide would be difficult to perform in a raster environment, unless pixel spatial resolution was small, which would negate some of the gains in processing efficiency. The end products of this project are at 250 m spatial resolution. The effects of simply eliminating the minimum width and area processes on the overall forest land area estimates were not investigated as part of this study.

For comparison, the vector methodology described in this paper was adapted for a raster environment, with one process altered and another process omitted. The process altered was the elimination of areas less than 120 feet wide. Instead, a minimum mapping size criterion was applied, which partially dealt with the 120 foot width requirement. The process omitted was the reallocation of housing density. All the data layers used in the vector-based approach were converted to a raster file format with spatial resolution of 30 m. The same basic procedures described above were followed, using the ERDAS Imagine software package.

Comparisons

Forest Land Area: Estimates of forest land area derived from this study's geospatial datasets were compared with FIA's plot-based estimates. Additional comparisons were made with estimates of forest land area derived from the 2001 NLCD (Homer and others 2007), the 2001 Forest Types Map (Ruefenacht and others 2008), and with FIA estimates of timberland – a major sub-component of FIA forest land.

For each state, countywide FIA estimates of forest land area were compared with modeled geospatial estimates to produce area weighted root mean square deviations (RMSD) using methods derived from Häme and others (2001):

$$RMSD_{rs} = \sqrt{\sum_i \frac{a_i}{A}\left(\hat{p}_{ir} - \hat{p}_{is}\right)^2} \qquad (1)$$

where a_i is the area of the ith county, A is the total area within a state (sum of a_is for all counties in that state), and $\hat{p}_{ir}$ and $\hat{p}_{is}$ denote the estimated proportion of forest land in the ith state obtained from the FIA sample plots (r) and modeled geospatial dataset (s) estimates.

Results

Differences in results derived from the raster and vector products were insignificant (table 2), but raster processing took only two days per state, as opposed to seven days for vector processing. These results support those of Wade and others (2003) who reported faster processing time with raster data, and ecologically insignificant differences in results. Subsequent results are reported only for modeling of raster geospatial file formats.

Table 2: Comparison of forest land area estimates (acres) derived using vector and raster GIS file formats.

State	Raster	Vector	Difference (Raster – Vector)	RMSD (Acres)	RMSD (Prop.)	RMSD (Percent)
Arizona	5,076,039	5,106,296	-30,257	11,209	0.0017	0.17
Minnesota	17,442,442	17,502,500	-60,058	21,082	0.0010	0.10
Montana	19,091,504	19,688,044	-596,540	33,000	0.0009	0.09
New York	18,309,622	16,839,980	1,469,642	33,880	0.0022	0.22
North Carolina	17,187,758	16,634,397	553,361	10,791	0.0006	0.06
Oregon	22,731,634	24,130,448	-1,398,814	79.867	0.0014	0.14

Figure 8 shows the per-state FIA estimates of forest land (FIA forest land) and timberland (FIA timberland) area compared to estimates derived from raster geospatial modeling of this study (GIS raster model), 2001 NLCD (NLCD01), and 2001 Forest Type Groups (ForTypGrp Map) datasets. Forest land area estimates from the raster model were substantially lower than FIA forest land area estimates for three western states (Arizona, Montana, Oregon), but were more similar for three eastern states (Minnesota, New York, North Carolina). However, all estimates were outside the lower and upper error bounds of the FIA forest land area estimate 95 percent confidence intervals. Modeled estimates were lower than 2001 NLCD estimates for all states, and lower than 2001 Forest Types estimates for all states except Minnesota, where the two were similar. By definition, timberland comprises a sub-component of FIA forest land area. For all states except North Carolina, FIA area estimates of timberland were significantly lower than estimates of forest land.

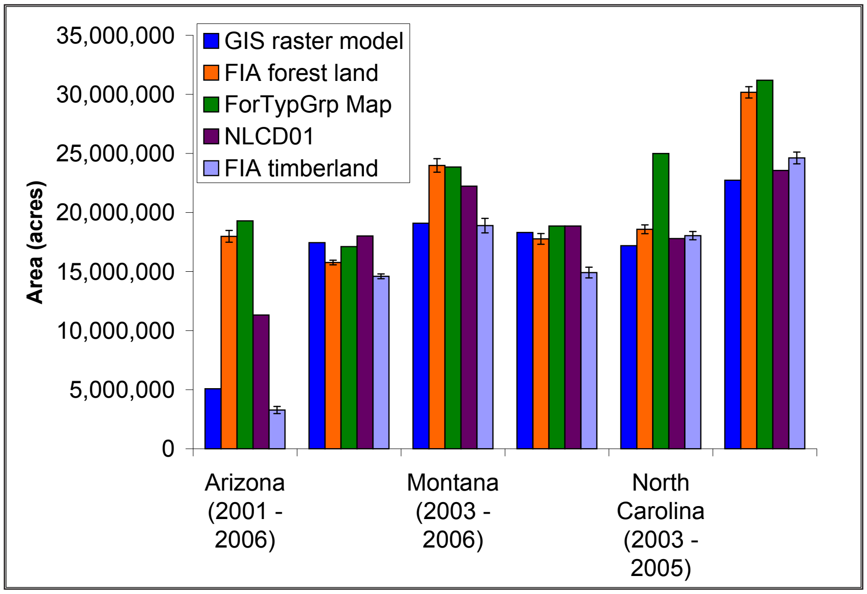

Figure 8: Estimates (in acres) of forest land area derived from the GIS raster model, FIA forest land, 2001 Forest Type Groups Map, 2001 NLCD; and FIA timberland area. Error bars for FIA forest land and FIA timberland show the 95 percent confidence intervals.

Figure 9 shows the RMSD between FIA estimates and raster GIS model-based estimates of countywide forest land area for each of six states included in this study. FIA forest land area estimates were in agreement with the forest land area estimates produced in this study. Arizona shows the largest RMSD, exceeding 3 percent, while Minnesota, New York, and North Carolina all had RMSD values below 0.5 percent. Montana and Oregon showed RMSD values between those of Arizona and the three eastern states.

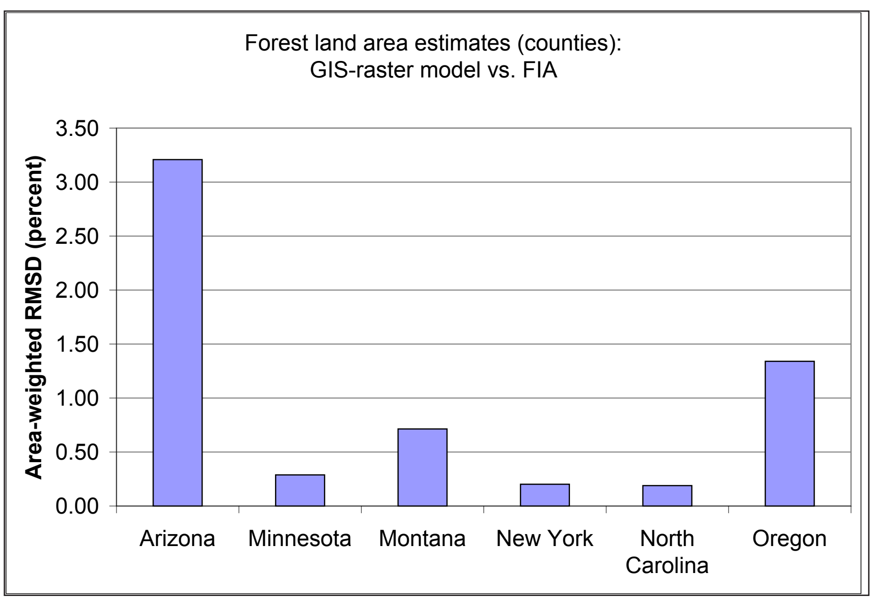

Figure 9: Area-weighted RMSD between FIA-based and GIS raster model-based countywide estimates of forest land area.

Discussion

Figure 8 reveals disappointing results in the raster GIS model-based estimates of forest land area for all states, with the possible exception of New York. One processing step in particular – applying a minimum canopy cover threshold of 25% – likely was a major cause of the discrepancy in estimates between FIA and the raster GIS model. A change in this threshold would greatly influence the resulting forest land area estimates. Nelson and others (2004) reported that mean VCF percent canopy cover varies substantially among states. Thus, considerable improvement in estimates is expected to result from optimizing the tree canopy cover dataset.

One of the goals of this project was to design an operational modeling framework where interchangeable pieces could be taken out and replaced with newer or more current data, or used for other spatial resolutions. Because the geospatial modeling procedure is now established and documented, it is possible to rerun the models with alternate data sources, and recalculate forest land area estimates, with resulting improvement in estimates of forest land area.

One of the major challenges with the methodology was the amount of time involved in processing geospatial databases in the GIS. For example, the computer processing time for each state spanned a minimum of seven days, which did not include analyst time required to obtain and transfer files, manage datasets, set up processes, etc. To process one state might require a total of two to three weeks. One of the reasons why the processing takes a considerable amount of time is due to the necessity of sub-setting the data layers into small subsets. This made it necessary to keep track of neighboring subsets, which was challenging. Extra processes needed to be incorporated to handle border issues, which significantly increased the processing time. Based upon our results, it is strongly recommended that future processing be performed in a raster environment, with modeling steps modified accordingly.

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